Fermilab

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The tolerance issues for FNAL BPM prototype

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Introduction

A cold L-Band cavity BPM prototype is being developed by AD Mechanical Support and Instrumentation and TD SRF. The design is based on dipole mode selective coupling [1]. The prototype has two design features: vacuum tight coupling slots with ceramic windows and four antennae to pick up a reference signal and simultaneously to load monopole mode, making its loaded quality factor comparable to that of dipole modes. The ceramic windows separate closed waveguides from the main BPM body and relax the problem of ultra-cleaning.

For BPM design and simulation CST Microwave Studio was used. General view of BPM model is shown in Fig. 1.

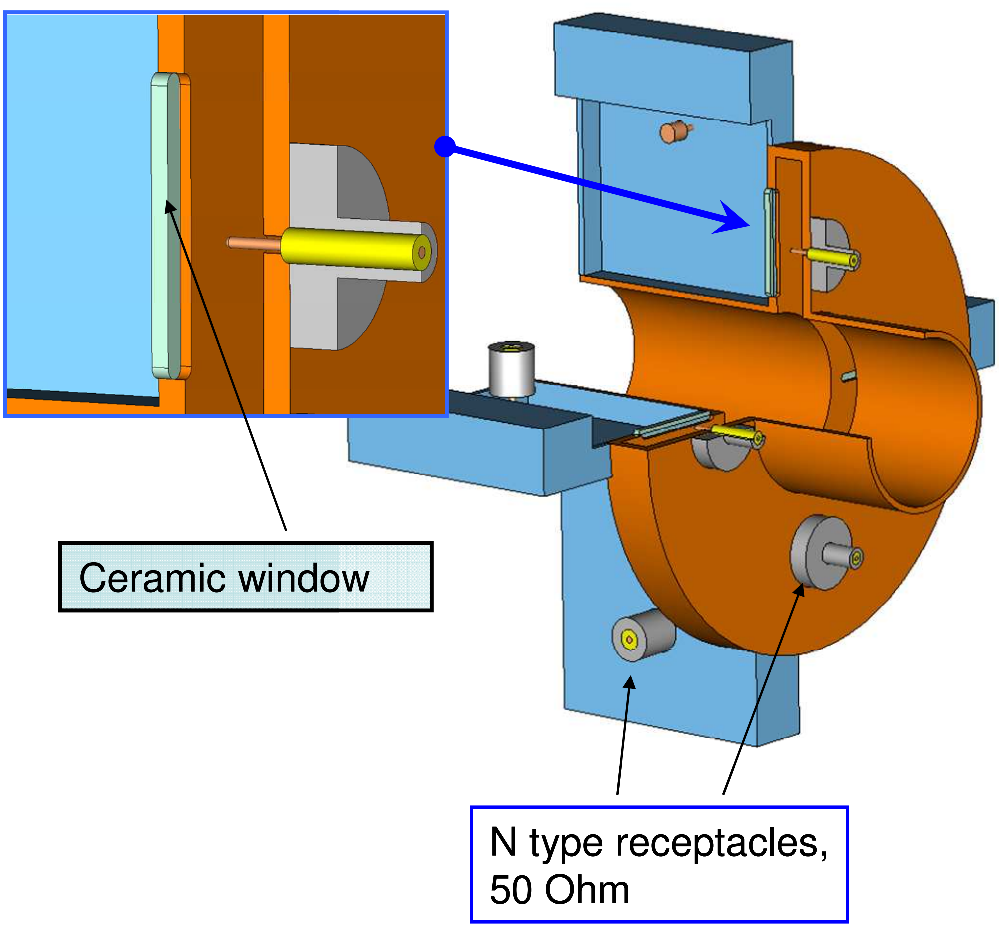

Figure 1. FNAL L-Band BPM prototype. The ceramic windows are bricks of alumina 96%. The pick-up feedthroughs are standard industrial parts.

Preliminary main design parameters of BPM are given in the table 1.

Table 1.

Monopole mode frequency, GHz	1.47
Dipole mode frequency, GHz	1.13
Loaded Q (both monopole and dipole)	≈600
Beam pipe radius, mm	39
Cell radius, mm	113
Cell gap, mm	15
Waveguide, mm	122x110x25
Coupling slot, mm	51x4x2
Ceramic window (ϵ=9.4)), mm	52x5x3

A certain progress has been made to study the critical brazing of the ceramic bricks into the coupling slots. RF studies are in advanced stage and a set of technical drawings is almost complete. Tolerances for the critical dimensions of the cavity and waveguides were specified to be 10 μm. However more clear understanding of some tolerance issues is still needed. It's important to study how machining errors induce leakage of the common (monopole) mode, create mode coupling and x-port to y-port coupling. It will help to develop tuning features and procedures to relax machining and assembling tolerances, which are extremely tight now.

General consideration of BPM parameter sensitivity to perturbations

It is very effective to consider BPM sensitivity issues analytically in parallel with time consuming numerical simulations. It helps to develop more clear vision of processes and saves time and efforts. Coupled mode and perturbation theory formulations of Maxwell's equations give a theoretically elegant and efficient way of describing small imperfections and weak interactions in electromagnetic systems.

$$\mathbf{E}(x,y,z)=\sum_{\nu=1}^{N} e_\nu \mathbf{E}_\nu(x,y,z) \qquad \mathbf{H}(x,y,z)=\sum_{\nu=1}^{N} h_\nu \mathbf{H}_\nu(x,y,z)\,. \tag{1}$$

The eigenfunctions are usually ortonormalized as

$$\int_V E_\nu E_n dV = z_0^2 \int_V H_\nu H_n dV = \begin{cases} W_{norm}, \nu = n \\ 0, \nu \neq n \end{cases},$$

where $z_0 = \sqrt{\mu_0/\varepsilon_0}$ – wave number of open space.

Standard time dependence of the electromagnetic fields is

$$\mathbf{E}(x,y,x,t)=\mathbf{E}(x,y,z)e^{i(\omega t+\varphi)}=\dot{\mathbf{E}}e^{i\omega t} \quad \text{and} \quad \mathbf{H}(x,y,x,t)=\mathbf{H}(x,y,z)e^{i(\omega t+\varphi)}=\dot{\mathbf{H}}e^{i\omega t}, \tag{2}$$

where complex amplitudes $\dot{\mathbf{E}}=\mathbf{E}(x,y,z)e^{i\varphi}$ and $\dot{\mathbf{H}}=\mathbf{H}(x,y,z)e^{i\varphi}$ are used.

Let's introduce a small perturbation ΔV in a cavity of volume V_0, so a new cavity volume is $V=V_0 - \Delta V$. It has been shown [2] that for small perturbations the relation between perturbed and unperturbed mode frequencies and fields can be described approximately by a system of linear equations (consider electric field only for simplicity):

$$\mathbf{Ae} - \omega^2 \mathbf{e} = \mathbf{0}\,, \tag{3}$$

where

$$a_{\nu\nu} = \omega_\nu^2 \left[1 + \frac{1}{W_{norm}} \int_{\Delta V} (z_0^2 H_\nu^2 - E_\nu^2) \Delta V \right],\ a_{\nu\mu} = \frac{\omega_\nu^2}{W_{norm}} \int_{\Delta V} (\dot{\mathbf{E}}_\nu \dot{\mathbf{E}}_\mu^* - z_0^2 \frac{\omega_\mu}{\omega_\nu} \dot{\mathbf{H}}_\nu \dot{\mathbf{H}}_\mu^*) dV\,,$$

and $\sum_{\nu=1}^{N} e_\nu^2 \approx 1$ for small perturbations.

Solving this system one can find mode frequencies $\tilde{\omega}_\nu$ of the perturbed cavity and expansion coefficients **e** for the perturbed fields. For our purposes we can make further simplification: assume that $\tilde{\omega}_\nu \approx \omega_\nu$, because for small perturbations the perturbed frequencies are very close to unperturbed ones. After this simplification one can derive from (3) a field of nth mode in the cavity with perturbation ΔV as:

$$\tilde{\dot{\mathbf{E}}}_n \approx \dot{\mathbf{E}}_n + \sum_{\nu \neq n} \dot{\mathbf{E}}_\nu \frac{\omega_\nu^2}{\omega_n^2 - \omega_\nu^2} \frac{1}{W_{norm}} \int_{\Delta V} (z_0^2 \dot{\mathbf{H}}_\nu \dot{\mathbf{H}}_n^* - \dot{\mathbf{E}}_\nu \dot{\mathbf{E}}_n^*) dV\,. \tag{4}$$

Analyzing this expression for the fields in perturbed cavity one can conclude:

1. In general a field of any perturbed mode is a sum of all unperturbed modes. The modes are all cross-coupled via couplings $k_{\nu n} = \int_{\Delta V} (z_0^2 \dot{\mathbf{H}}_\nu \dot{\mathbf{H}}_n^* - \dot{\mathbf{E}}_\nu \dot{\mathbf{E}}_n^*) dV$. So, when on-axis beam passes through a BPM cavity with imperfections, it excites directly monopole mode and other modes with non-zero electric field on axis. It's not obvious, but the dipole modes and other modes with zero electric field on axis would be excited in a perturbed cavity as well, if corresponding coupling $k_{\nu n} \neq 0$. Some part of beam power would go through monopole mode into excitation of these modes and creating parasitic signals in output ports. Looking at different angle, we may say that perturbed monopole mode has got dipole (and many other) components. On the other hand perturbed dipole modes get monopole component.
2. Actually perturbation ΔV is a sum of local perturbations ΔV_i. For example, all coupling slots may have different sizes, orientations and locations, therefore each of them will contribute its own perturbation. The perturbations may cancel each other and then corresponding mode coupling vanishes, and that points at the tuning possibilities. Theoretically an artificial perturbation may be introduced into the cavity to eliminate some particular couplings. The problem is a right choice of place and volume for such tuning perturbation to avoid deteriorating of BPM parameters or/and creating new unwanted couplings.

MWS simulations of some specific perturbations of BPM cavity have been performed to illustrate these conclusions and to estimate significance of different kinds of perturbations.

Numerical simulations of different perturbations

Simplified model of BPM prototype.

The model of FNAL prototype BPM to study the influence of cavity imperfections on resolution limits has been simplified to ease the simulation efforts. Particularly, the model does not have ceramic windows in the coupling slots, the slots are of rectangular shape, and the pick-up antennae for monopole mode are not present. To avoid problem with matching the coaxial feed-through receptacles in the waveguides have been removed and replaced with waveguide ports.

The BPM parameters changed due to these simplifications, but they were close enough to that of the prototype to bring right qualitative results. So, no attempt has been made to restore exact design BPM parameters. Besides, the most critical simulation results have been checked on the full model.

The general view of the model is shown in Fig.2a. In addition to the waveguide ports the model has been also provided with electric field probes in the waveguides (Figure2b) and magnetic field probes along coupling slots (Figure 2c) for additional transient field indication in these particular points. The ports and the probes are clockwise numbered as shown in 2a. Excitation of electromagnetic modes in BPM has been provided with port #5 in beampipe (Figure 2d, port with magnetic field distribution of TM_{01} mode in circular waveguide is shown).

In MWS the discrete ports and discrete sources of current and voltage are available. They are more appropriate for beam simulation, but their effect has additional complications and impacts. So, meanwhile the circular waveguide port is used to get clearer picture.

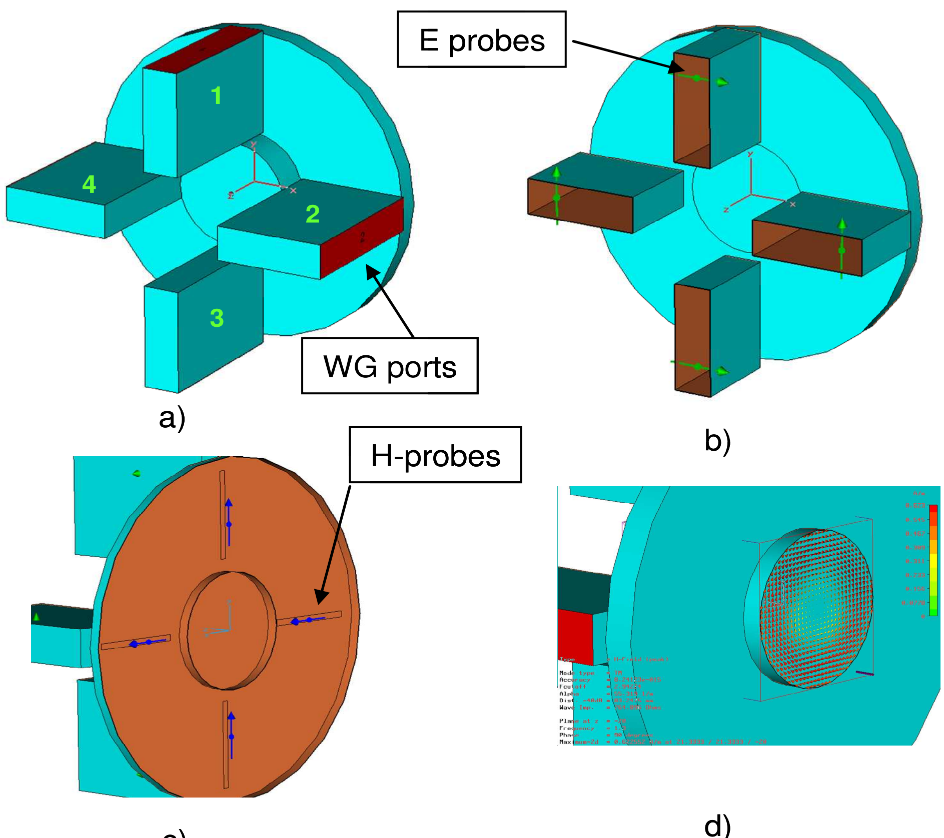

Figure 2. a) General view of BPM model with output waveguide ports; b) Location of electric field probes; c) Location of magnetic field probes; d) Input waveguide port.

In the simulations monopole mode TM_{01} was excited through cylindrical waveguide port #5 in beam-pipe and transmission (S parameters) of monopole mode into waveguide ports was indicated. Since pure monopole mode is excited in the cavity, any signal that reaches waveguide ports should be considered as a contamination. The following perturbations and combination of perturbations have been simulated:

1. No perturbations.

We can see identical signals from monopole mode in all output ports and correspondingly S15=S25=S35=S45. The signals are very weak – actually it's just a noise. At dipole frequency of 1.47 GHz attenuation is ≈-130 dB. Only one S-parameter for output port 1 is shown as S15_1 in Fig.3. S15_1_AR is the same curve after auto-regressive filtering has been applied.

2. All slots are rotated by 2° around their centers.

The cavity is still axial symmetric. The signals are equal in all ports, but they are more powerful - the attenuation is -70 dB at frequency 1.47 GHz. We can say that there is a penetration of monopole mode into the waveguides. Note the influence of waveguide cutoff at 1.37 GHz. As in previous case only one S-parameter is shown in Fig.3 and marked as S15_2.

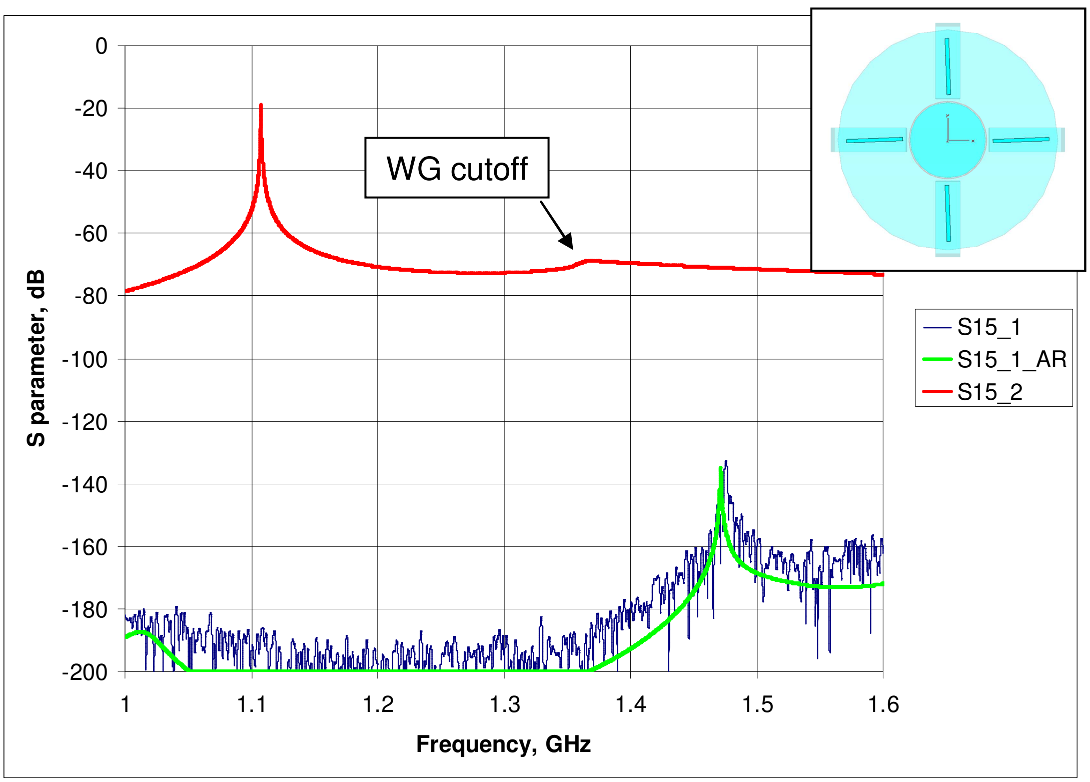

Figure 3. Spectra of output signals without any perturbations (S15_1) and with all coupling slots rotated by 2° (S15_2).

3. Only one slot #2 is rotated by 2°.

For this perturbation we can see the signals in all output ports and all spectra have a resonance at dipole frequency 1.47 GHz, which exceeds symmetric perturbation case by 20 dB (see Fig.4). Character of signal spectrum is different for different ports. The signal in rotated port 2 consists of directly penetrated monopole mode and dipole mode excited due to the mode coupling. So, S15_3 coincide with symmetric case S15_2 everywhere except dipole frequency. In ports 1, 2 and 3 we see dipole mode signals only, because the slots are radial and reject direct penetration of monopole mode. It's easy to figure out that the coupling between dipole and monopole modes is zero, when the slots have absolutely equal and axially symmetrical deviations from the nominal parameters. Note, that such symmetry eliminates coupling between modes, but does not prevent direct penetration of monopole mode through the tilted slots.

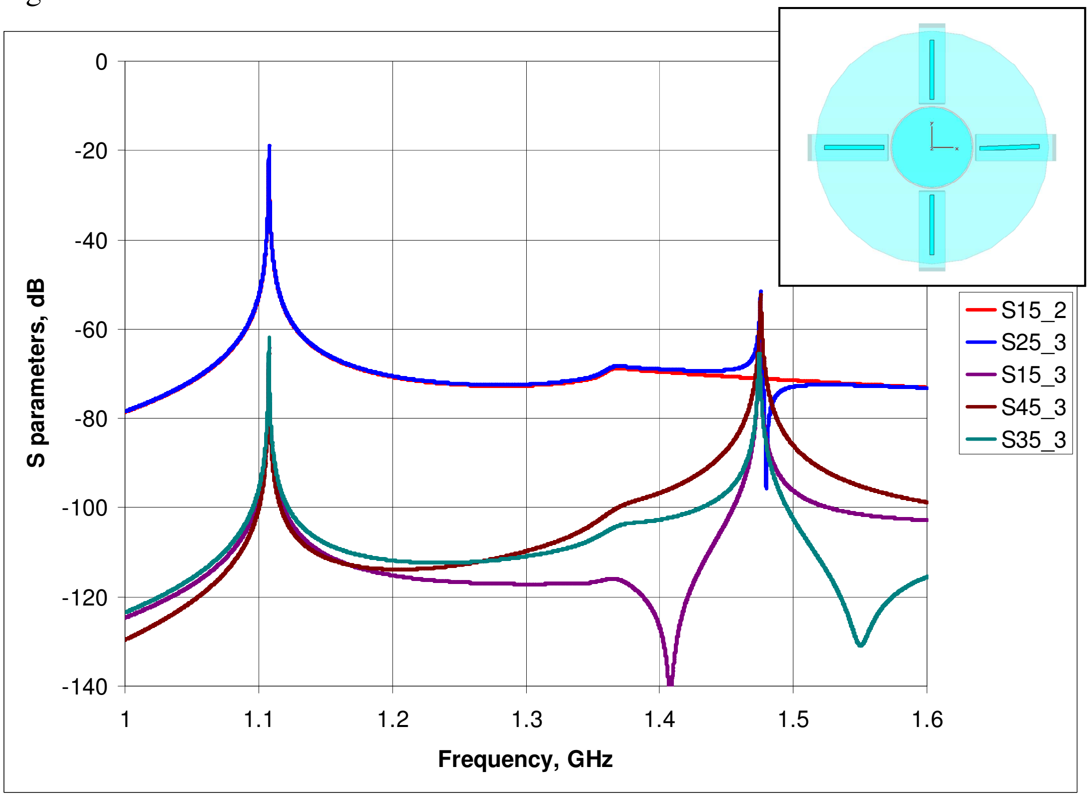

Figure 4 Comparison of symmetrical perturbation (spectrum S15_2) and asymmetrical perturbation by rotation of one slot #2 (spectra S15_3, S25_3, S35_3 and S45_3).

4. Non-symmetrical perturbation on periphery

The perturbation (a dent - hemisphere of 5 mm diameter) is placed in plane Y (ports 1 and 3) in front of slot 1. This perturbation couples monopole mode with dipole mode in X-plane only (output ports 2 and 4). Consequently, we observe the resonant signals only in plane X (spectra S25_4 and S45_4 in Fig.5). The signals in Y-plane ports are at noise level.

5. Symmetrical perturbations on periphery

Four dents are made symmetrically as shown in inset in Fig.5. Opposite dents are in dipole fields of opposite signs, therefore the monopole-dipole coupling coefficients mutually eliminate each other. The simulation shows the signals in all ports at noise level. At the same time there is a frequency shift for dipole and monopole modes. So, such dents could be used at least for frequency tuning, but the problem is symmetrical and equal deformation of opposite dents.

CONCLUSION

So, we may conclude, that monopole mode can contaminate the useful signals in waveguide ports by two ways (which can combine):

1. There can be a direct penetration of monopole mode through the slot with deviations, because the slot rotation (or other similar imperfections) result in non-zero projection of the azimuthal magnetic field of the monopole mode along side the slot, causing coupling of the monopole mode to the waveguide.

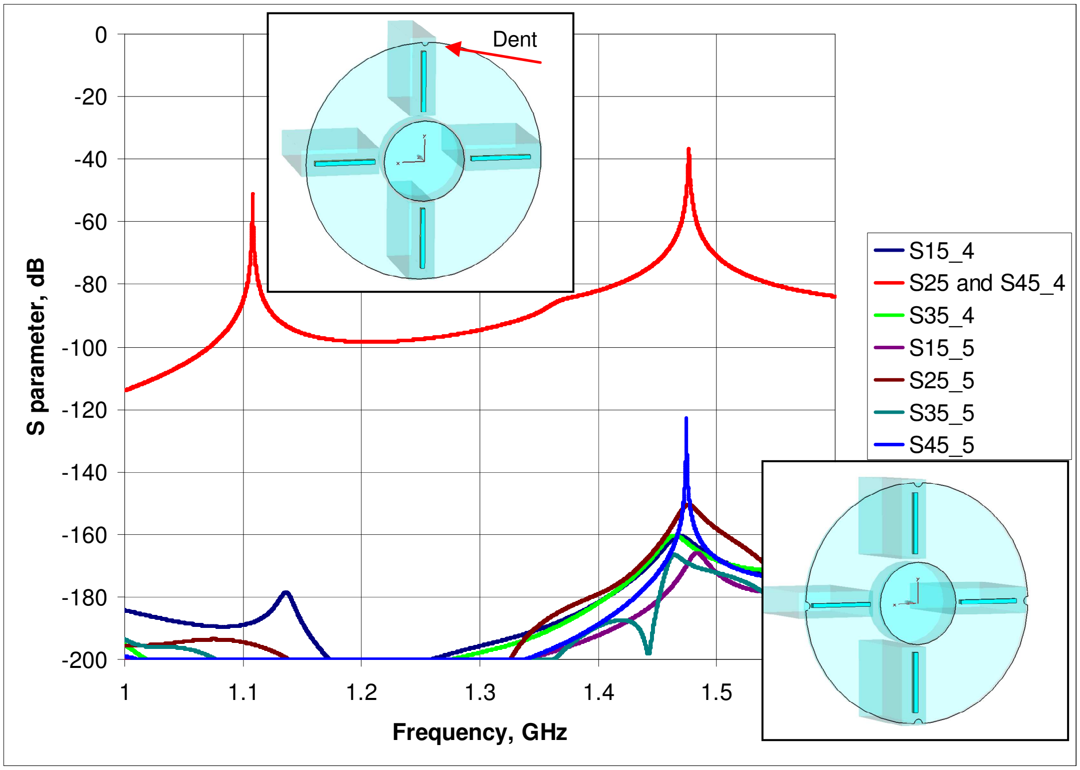

Figure 5 Spectra of the port signals for perturbation created by one dent and by four symmetrical dents (simulation of frequency tuning).

2. In case of asymmetrical perturbation there can be a coupling between dipole modes and monopole and other modes. Dipole modes are excited via this coupling and generate parasitic signals. Apparently, the perturbations that create asymmetry are more dangerous for BPM performance because of resonance character.

The frequency tuning with the dents (as designed for prototype) is possible, but the problem of maintaining the cavity symmetry is serious.

References

1. Zenghai Li et all, “Cavity BPM with Dipole-Mode-Selective Coupler”, PAC, 2003, Portland, USA
2. A.G.Gurevich, “Hollow resonators and waveguides”, Moscow, “Sov. Radio”, 1952